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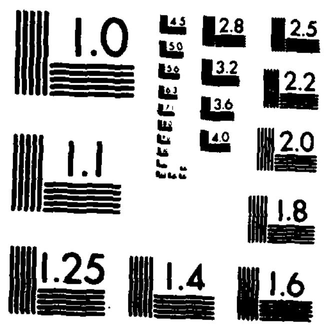

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Explaining Complex Engineered Devices

Daniel S. Weld

November 1983

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Personnel and Training Research Programs

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This paper presents the outline of an algorithm which generates summary explanations of and answers questions about complex engineered devices. The algorithm uses two domain models: an expert model of the machine, and a model of the student's device understanding. Also required is an inference engine which can perform qualitative simulations of the device engine from the expert model. Given these prerequisites, the algorithm recursively describes the device in a series of ever more detailed passes.

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In each pass the device is depicted with a strict sequence of topics: the device's role, function, structure, and then its mechanism. The explanatory algorithm is interesting not only for its potential utility in computer aided instruction but also for the constraints it sets on the contents of an expert tutor's mental model of an engineered device.

Abstract

This paper presents the outline of an algorithm which generates summary explanations of and answers questions about complex engineered devices. The algorithm uses two domain models: an expert model of the machine, and a model of the student's device understanding. Also required is an inference engine which can perform qualitative simulations of the device engine from the expert model. Given these prerequisites, the algorithm recursively describes the device in a series of ever more detailed passes. In each pass the device is depicted with a strict sequence of topics: the device's role, function, structure, and then its mechanism. The explanatory algorithm is interesting not only for its potential utility in computer aided instruction but also for the constraints it sets on the contents of an expert tutor's mental model of an engineered device.

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1. INTRODUCTION

A critical facet of instruction is the ability to explain. In the domain of instruction regarding complex devices like steam propulsion plants or automotive engines, this explanation must create a detailed and correct model of the device in the mind of the student. Depending on the instructional goals, the explanation may tailor the model to different tasks like device design, operation, or troubleshooting. But many problems are independent of application: What is the best way to transfer a given model to the student? How can a tutor firmly graft the device model onto the student's existing models?

1.1 Goals and Methods

Our goals in this research were to develop a generic algorithm that could be used to explain a wide variety of engineered devices and to determine what types of expert knowledge were required to generate these explanations. We view this as an attempt to describe a high level "road map" of the types of explanation used and how they fit togther. Thus, we have attempted to describe the algorithm in enough detail so that we could understand what could be done generatively and what required more research.

Our approach was to analyze the explanations in various texts [RD 81, BNP 71, BNP 70]. Once a rudimentary algorithm was

developed, we used it to generate an explanation of an internal combustion engine and sought reader feedback. A question taxonomy was derived from the explanation theory, and was informally tested by successfully classifying an external set of questions.

In our view, explanatory text generation is a two step process: This paper discusses the first step, a structural algorithm that uses specific knowledge of a device to generate a graph representation of its explanation. A second step (not considered here) takes the explanation graph and produces a natural language version of the explanation.

1.2 Limitations

Since our research is closely related to work in the varied areas of natural language, computer aided instruction (CAI), and qualitative reasoning, we felt it was important to impose some strong restrictions.

- We are presently concerned with "good" explanations rather than with the whole range that occur naturally in dialogs. Although "good" is still a subjective judgement, we have attempted to select and model explanations that are clear and focused.
- We are interested in explanations designed for general learning. We have not considered explanations designed for read-along activity or specific procedure acquisition.
- We restrict ourselves to written explanations even though diagrams are obviously very important in the description of complex devices.

- o We consider only the structural elements of explanation, i.e. the generation of an intermediate, graph form of an explanation. We will not discuss the nature of the intermediate form nor the production of natural language from that graph structure. For simplicity, however, all our examples will be in English, not an intermediate form.
- o We consider only the explanation of human engineered mechanical devices. Although many of our techniques may apply to other domains, we have not verified this.
- o We assume that the student model is a subset of the expert model. Although it would be useful to utilize information about common misconceptions while generating explanations, we have avoided the issue for now.
- o We present only a rough version of a theory of explanation. As there is no computer implementation, the details of the algorithm's behavior are untested.

1.3 Explanation Algorithm Summary

The trick to a good explanation is the use of repetition at multiple levels of detail. First the device is described at a high level of abstraction; then more and more detail is added to the initial context. This detail is added in levels that correspond to the subcomponent layers in the model's hierarchical description. At each level the algorithm follows the same general procedure: describing a component by explaining its *role* in the whole, its *function*, its *structure* in terms of subcomponents, and its *mechanism*, i.e. how the component's structure produces its function.

Consider the power train of an automobile. The first pass of the explanation is at the top level.

1.3.1 Role

We describe the power train's role, i.e. the function that it plays in its *structural context*. Since the context of a power train is the drive system of the automobile, we generate the following sentence:

> **The power train transmits the rotary motion that is produced by the engine to the rear wheels where it is used to propel the car.**

1.3.2 Function

We describe the power train's function, i.e. its behavior as a black box, if this function is different from its role.[1] In this case the function, "to transmit and modify rotary energy", is so similar to the role that it is pruned from the explanation.

1.3.3 Structure

We describe the power train's structure, i.e. what subcomponents it is made of and how they are connected. As each subcomponent is listed, its role is given. We generate:

[1]The distinction that we draw between role and function can be confusing. Although the two concepts are often quite similar, the context of an object is important to its role, but does not affect its function at all. In a sense, the function of an object is *what* the object does, and the role is *why* it does it. An example will help to clarify the distinction. Consider two identical electric chimes: one part of an alarm clock, and the other built into a automobile. The function of the two chimes is identical, to make a noise. But the roles are different because they depend on context. In one case the role is to awaken a sleeper, and in the other case the role is to remind passengers to buckle up.

> The power train has five parts connected in sequence. The clutch is a switch which can disconnect the power of the engine from the wheels. The transmission controls the power and speed of rotation. The propeller shaft allows the power train to stretch on bumpy roads. The differential distributes power as required to the two driving axles. And the driving axles propel the wheels.

1.3.4 Mechanism

Finally we describe the power train's mechanism, i.e. how its structure produces its function. Since device mechanism is often the most difficult aspect of the explanation for students to understand, there are numerous techniques for generating this type of explanation. The most effective kind is the physical causal chain, which can be created using qualitative simulation [Forbus 81]:

> When the engine causes the clutch input shaft to rotate, the clutch transfers this rotation to the output shaft if it is engaged. The rotating output shaft enters the transmission which causes the propeller shaft to rotate, perhaps with a different power/speed ratio. The propeller shaft drives the differential through a flexible connection. The differential divides the input power among the two driving axles which turn the wheels.

At this point the algorithm recurses to explain the clutch, transmission, etc. It terminates when all the unexplained subobjects are marked as already understood in the student model.

1.4 Question Answering

Although the ability to generate complete summary explanations is useful, the skill of answering questions has greater demand. A question taxonomy based on the role, function, structure, mechanism device breakdown suggests a simple extension to the explanatory algorithm. For each of the fifteen question catagories discovered, answers may be generated by running selected phases of the algorithm. For example, the question "What parts does a bicycle have?" is in the *substructure of object* class. It is easilly answered by running the structure phase of the explanation algorithm on the bicycle object.

1.5 Paper Overview

The rest of the paper is divided into three sections. In section two, we describe the recursive explanation algorithm in more detail, discussing each phase (role, function, structure, and mechanism) in turn. In addition, we present certain heuristics that make the explanation more natural. We also discuss the requirements of the algorithm, especially the constraints that the algorithm places on the expert model. In section three, we describe a taxonomy of questions and show how this taxonomy facilitates the extension of the explanation algorithm to answer specific questions. Finally we conclude, in section four, with comments about possibilities for future work.

2. THE EXPLANATORY ALGORITHM

We will consider three topics in this section: the overall pattern used by the explanation generator at one level of recursion, methods for selecting appropriate viewpoints in an explanation, and heuristics for modifying the intermediate explanation graph to produce a more natural text.

2.1 The Pattern

Because the explanation algorithm is recursive, it is important to understand how it terminates. When called to explain an object, the algorithm describes four aspects of that object (i.e. its role, *function*, *structure*, and mechanism) in order, before recursing (depth first) to describe each of the object's structural subobjects. If the student model indicates that the student already understands one of the subobjects, then the algorithm does not repeat the subexplanation. Thus the algorithm terminates when all referenced subobjects are marked as known in the student model.

2.1.1 Role

The role of an object is its purpose in the overall context of its environment. For example, two identical light bulbs would have different roles depending on their use: either to illuminate the road in front of a car or to scare away burglars who trip an alarm.

Roles may be decomposed into two categories. *Positive roles* facilitate the attainment of a desirable goal. For example, an engine aids the goal of making a car mobile. *Protective roles*, on the other hand, help prevent undesirable events, e.g. as in the role of a lubrication system.

When reasonable, the description of an object's role is accompanied by a statement of the boundary conditions (i.e. contextual boundaries) that limit the object's ability to fulfill its role. The range of valid operating temperatures for a device is a common example.

2.1.2 Function

The function of an object is its description as a black box independent of context. For example, the function of a light bulb is to emit electromagnetic radiation. When an object's function depends highly on its context (as in the power train), the function becomes almost indistiguishable from the object's role. In these cases it is best to omit the functional description from the pattern.

Objects usually have *multiple functionality*, although it is common for only one to perform a useful role. For example, a light bulb generates both visible light and heat. Although the second function (i.e. heat production) is frequently considered a side effect, we do not discriminate between functions except for

the relevance to roles. This unbiased attitude is especially useful in cases where two different functions of identical objects perform useful roles. For example, the different functions of a light bulb might be used to illuminate a room or warm an incubator.

In addition, engineered objects often have *ancillary functionality* which is not mentioned explicitly, but may be referenced later to explain certain structural features. Examples of ancillary functionality (as distinguished from explicit goal functionality) are: easy or inexpensive construction, easy or inexpensive repair, easy design relative to an evolving design history, and safe operation. Often a new viewpoint is required to motivate ancillary functionality; brake lights would seem senseless unless one realized that there would be more than one car on the road.

2.1.3 Structure

The structure of an object is the set of subobjects which form the object and the connections between them. All paths for functional interaction between (blackbox) subobjects must be mentioned as connections. In almost all the explanations that we studied, diagrams were heavily used to convey structure. Thus it is unfortunate that we were forced to ignore the dynamic design of diagrams; hopefully future work will address this important issue.

As each of the subobjects is listed, it is distinguished from the others by its role in the context of the object. Sometimes it is useful to include an extra distinguisher that creates a vivid image in the student's mind. For example, to distinguish the automotive brake system [RD 81] says: "Each time a car comes to a complete stop from 60 mph, the brakes generate enough heat to boil a half pint of water". Dynamic generation of these facts does not seem feasible, because of the vast amounts of cultural information necessary to judge whether one is interesting and vivid. However, selected facts could be stored in to the expert model and retrieved by the algorithm.

Choosing the best order for listing the subobjects is an instance of the larger problem of selecting appropriate viewpoints. For this special case a useful heuristic is to order the subobjects by their position in a causal chain; the main advantage of this ordering is its fit with eventual mechanism explanations. See the power train example above.

Although analogies are most useful as techniques to explain device mechanism, they are best initiated by a concrete comparison in the structural phase of the explanation because they become more real in the student's mind. Thus the algorithm should attempt to restrict its selection of subobject description to attributes which reinforce any analogies which will be required by the mechanism phase.

2.1.4 Optional: Global Constraints

Sometimes it is useful to add an extra phase to the explanation process. Whenever a mechanism relies heavily on some physical law (as does the internal combustion engine on the ideal gas law) or global constraint (perhaps spatial), this fact should be discussed. This phase wasn't mentioned above, because often it isn't necessary. However when a mechanism does depend on these constraints, early explanation of them allows more effective arguments and alternate viewpoints especially for sophisticated readers.

If appropriate to the device in question, relevant constraints could be derived from the process model of the qualitative process (QP) simulation engine and explained explicitly.

Constraints (i.e. $PV = nRT$) are best illustrated with the physical causal explanation form,[2] augmented by a statement that the actual effect is synchronous. For example:

> **There is a law of physics which states that for any quantity of gas, the product of volume and pressure is proportional to the temperature. For example, if the volume of gas is fixed, then a rise in temperature would force the pressure up. Naturally, this process is continuous so the equality always holds.**

---

[2] This method for explaining device mechanism was used in the power train example above and is described in detail below.

2.1.5 Mechanism

A device's mechanism is the manner in which the device's structure produces its function. Since a device's mechanism is often the hardest aspect for students to understand, it is important to utilize a variety of different specialized and effective explanation types: statement of rationale, physical causal, local constraint, and analogy. Methods for choosing appropriate viewpoints are discussed in the next section.

2.1.5.1 Statement of Rationale

The simplest mechanism explanation is a statement of the form: structure implements function [because justification] [Weiner 79]. This method is most useful when a single structural subobject is solely responsible for producing a single function (unfortunately, the situation is usually more complex and requires more sophisticated explanation methods). In these simple cases, a justification is often not required. If it is there are several types to choose from:

- If the function achieves a protective role, then a good technique is to postulate the absence of the structure and show how a disaster would result. E.g. "If there were no lubrication system,...".

- Selection from alternatives is a simple justification method for functions that satisfy positive roles. All the possible structures that could produce the function are listed and shown to be inferior to the chosen structure [Weiner 79].

If a more complex justification is needed, then a different method of mechanism explanation will prove superior.

2.1.5.2 Physical Causal

The physical causal method is probably the most common and effective type of explanation for mechanical devices [Stevens 81]. In a physical causal explanation, the interactions of structural subobjects are depicted as causing a temporally ordered chain of events that results in the production of the object's function, either as the last element of the chain or by net effects of members of the chain. For an example of this method, see the mechanistic description of the power train in section 1.2. An explanation of a feedback system is another example.

Implementation of qualitative simulation techniques that are capable of producing causal chains for this type of explanation is an area of active research: [Forbus 83, Forbus 81, de Kleer 82a].

The effectiveness of the physical causal explanation type is somewhat surprising since this method depicts the device mechanism at times incorrectly. The temporal order of the causal chain is often fictitious and sometimes flows and forces are reversed from actuality [Stevens 81]. To compensate for these inaccuracies, the physical causal method is often followed by a local constraint explanation type.

2.1.5.3 Local Constraint

The local constraint method is an explanation type which is

specially useful in conjunction with a physical causal description. Specific temporal or spatial constraints, ignored by the causal description, are exposed by this type of explanation. When discussing a crankshaft, for example, we might say:

> **Because the connecting rod is attached to the crank on the crankshaft, it must describe a circle when the piston moves up and down.**

Temporal constraints are most commonly used to state that two events (often widely separated by the causal chain) happen at the same time.

2.1.5.4 Analogy

Analogy is the most expressive explanation type, but also the most difficult to automate. To dynamically generate useful analogies, a tutoring system would need extensive models of numerous different domains; ideally the student model could drive analogy by suggesting different analogy targets depending on student background. Unfortunately, this seems too difficult to be practical in the near term. However, representations for a few common concepts similar to the device domain could be stored in the tutor and used to generate a limited number of useful analogies. The structure mapping theory [Gentner 82] could aid the process of explaining these analogies by marking the attributes most deserving of emphasis. To be most effective an analogy should be initiated in the structural phase of the

explanation so that the mapping between structural elements is concrete. Given that base, the behavioral similarities can be exploited more convincingly.

2.2 Viewpoint Selection

The problem of selecting the best *viewpoint* from which to view a device is a difficult and unsolved issue. The choice of perspective is critical because different perspectives support different inference and reasoning methods. For example a pump may be viewed as an energy sink, a cause of liquid flow, a pressure transducer, and also as a device with two ports. Each of these views is useful, but for different reasons: when concerned with energy conservation, it would be foolish to consider the pump as a two port device.

Multiple viewpoints often reinforce each other in a helpful manner and sometimes it is necessary to change viewpoints as an explanation progresses. Although the importance of a good viewpoint affects the structural description, it is most obvious in the mechanism phase. Proper perspective is essential to demonstrate how a given structure implements different functions, especially ancillary functions.[3] It seems likely that the heuristics for choosing appropriate viewpoints are domain

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[3] I.e. two different viewpoints are required to explain how an engine produces power and how it is easy to repair.

dependent. However, during our study of internal combustion engines, we did observe several that seemed more generally useful.

- Cycles, like the steam loop in a steam power plant or the four stroke cycle in automobiles, are a very pointed clue. If a cycle is found in the device's mechanism, a close check should be made to see if conservation of mass applies; it is a powerful constraint. Repeated cycles of discrete events (like the four stroke cycle) can be useful, because they allow one to use Extrapolation to generate a continuous model from the discrete model [Weld 83]. This continuous model may then be simulated with techniques like Limit Analysis [Forbus 83], providing higher level information (e.g. net effect over time or energy flow through the system) about the original system.

- Generalizations provide an easy way for students to remember concepts. If it is possible to consider several objects as instances of some generic object, then expressing that abstraction as a viewpoint on the system is likely to be helpful.

- If the device manipulates "stuff" (e.g. steam, water, oil...), then it is often useful to look to see if the stuff undergoes state changes or if the stuff acts as a transport mechanism (i.e. steam carries energy). In these cases a direct look at the stuff involved is often a useful viewpoint. If state changes are involved, then the perspective of stuff as an aggregate which obeys statistical laws is sometimes useful [Stevens 81].

2.3 Assorted Heuristics

By recursively describing a device's role, function, structure and mechanism, we can generate coherent explanations for many cases. However, certain heuristics can improve the readability of the generated text.

2.3.1 Path Descriptors Punctuate Level Changes

Whenever the recursive nature of the explanation algorithm causes a level change in the explanation graph (i.e. after one subobject is explained, the algorithm pops up to explain the next subobject), a path descriptor should be inserted to help the reader locate himself in the overall explanation structure. These path descriptors may take various forms: section headings, hierarchical paragraph numbering, highlighted figures, or introductory sentences.

For example, after the top level description of the power train in section 1.2 above, each of the components (i.e. clutch, transmission, ...) would be described in turn. After describing the clutch and its parts, the algorithm would perform a level change and begin to discuss the transmission. This change should be emphasized by a new paragraph that starts with the following path descriptor: **"The transmission is the part of the power train which..."** Path descriptors restore the student's context, reinforcing the structure of the whole explanation, and preparing for more detail. For information of the use of path descriptors in natural text, see [Weiner 79, Reichman 81].

2.3.2 Variation

Another heuristic helps eliminate reader boredom by increasing the variability of the generated explanation in ways

that do not compromise its clarity. This heuristic could be implemented as a demon which notices statements which have been repeated during successive recursive calls to the explanation algorithm. If the repeated areas are close together, then the demon changes the second statement by adding more detail. Except for the case of overlap between an object's role and its function, the desire to eliminate redundancy may not be allowed to cause deletions from the intermediate graph which might affect explanation clarity. By adding more detail to the second instance of a repeated statement, student boredom is reduced in an informative manner.

2.4 Algorithm Requirements

To generate explanations of a specific device, the algorithm needs knowledge of the device (an expert model), a way to predict device behavior (an engine for qualitative simulation that uses the expert model), and knowledge of the audience (a student model). One of the more interesting results of our construction of this algorithm is a better view of the necessary structure of these components.

2.4.1 Expert Model

Since the goal of an explanation is to give the student an expert model of the device in question, the nature of an expert model is an important issue. We believe that an expert model has

five critical characteristics; it must be simple, inspectable, runnable, modifiable, and hierarchical.

- A simple qualitative model facilitates student reasoning and recall. To achieve this simplicity, correctness should not be sacrificed, although completeness often must be.

- If an entire model is inspectable, then the details of any part may be used to reason about the device as a whole. This quality is essential for question answering and other types of reasoning.

- We call a model runnable if it can be used to simulate the qualitative behavior of the device. This predictive ability is required for many mechanism explanations and is often useful for problem solving in general.

- The model should be modifiable so the student can use it as a base for models of faulty devices or for similar devices. To allow effective modification, the model must distinguish between structure and function [Davis 82]. This necessary distinction is also called the "No Structure in Function" principle [de Kleer 82b]. The functional (or behavioral) description of device components may not reference the overall function of the device.

- The model must be organized in a hierarchical fashion, as is a frame system [Minsky 75]. This allows description and simulation at varying levels of detail and accuracy which is important for complex devices.

2.4.2 Qualitative Simulation Engine

To explain the mechanism of a device (i.e. how its structure implements its function), it is often necessary to be able to predict the behavior of the device. Considerable research [Forbus 83, de Kleer 75, de Kleer 82a, Simmons 83, Kuipers 82, Collins 82] has been done on programs which are capable of this type of qualitative simulation given an expert model. We are especially

interested in the more specialized work on the application of these techniques to the generation of mechanism explanations [Forbus 81, de Kleer 82b]. In this paper we assume the existence of an engine for Qualitative Process (QP) theory as described in [Forbus 83].

2.4.3 Student Model

An ideal tutor would have a wide knowledge of a student's background in different fields (to aid in analogy selection) and knowledge of common misconceptions that a student might make as well as a record of the specific facts that the student had learned about the device in question. We have, however, ignored these complexities for the present; instead we take a simpler view of the student model. The explanation algorithm does not utilize information about common mistakes but assumes that the student's understanding is simply a subset of the expert's. We hope, in time, to investigate the ramifications of a richer student model.

3. ANSWERING QUESTIONS

The rough algorithm presented above works well for situations which require a complete summary description of the device. We believe that any general explanation algorithm should also support the ability to generate focused fragments of a complete summary in response to a question.

In this section we discuss a taxonomy that splits the set of possible questions into classes so that all questions in a given class may be answered in the same way. Generic answers may be generated for each class simply by pruning unnecessary material from the complete summary answer. This method takes full advantage of the highly structured nature of the general explanation algorithm.

3.1 Possible Taxonomies

We considered three different taxonomic schemes based on the following concepts, respectively: interrogatives, question meaning, and answer meaning. The last proved most suitable.

3.1.1 Interrogatives

The classification of questions on the basis of the interrogative used (i.e. why, where, what, how, who, which, when) is unsatisfactory, because the decomposition is almost unrelated to the meaning of the question or its answer. For example,

consider the two questions: "How far is it from Boston to New York?" and "What is the distance between Boston and New York?". These questions should clearly be answered in a similar manner, yet the interrogative classification separates them.

This isn't to say that knowledge about interrogatives is useless in question answering; clearly a question parser must reason at this level. However, in this paper we are concerned with the semantic structure of questions and explanations, not their syntax.

3.1.2 Question Meaning

Another approach is to analyze a large set of questions and attempt to classify them according to their meaning. Although this alternative seems good initially, it is hard to implement due to the problems in finding a useful classification of the "meaning" of each question. There are too many reasonable decompositions.

3.1.3 Answer Meaning

The approach we used relies on the fact that each question uniquely specifies the factual content of a correct answer. Thus to classify questions we first classify all meaningful statements about the device and then for each statement consider the domain of questions which would produce that statement as an answer. This technique was used to categorize questions in [Belnap 63]

but with a different (and for our purposes, useless) answer taxonomy.

We use the role-function-structure-mechanism device view to classify possible answers. This produces a question taxonomy that is especially helpful in generating answers using our algorithm.

3.2 Question Taxonomy and Answer Generation

We will display the question taxonomy by presenting a generic answer fact as a heading for each question class. These classes fall in four groups which correspond to the explanation part (i.e. role, function, structure, or mechanism) that the grammatical object of the answer sentence instantiates. For each question class an example question will be provided and the explanation method will be discussed if it is different from the answer heading. In many cases this answer method will generate a longer and clearer explanation than the simple answer heading.

For each question category, there are really three possible types of questions:

1. What is it?
2. Why isn't it this instead?
3. How else could it be done?

For example, consider the question category defined by the generic answer heading: "Structure implements function". If we

take structure to be a light bulb, function to be the emission of visible light, and assume some specific context like the interior cabin of an automobile, then we get the following three questions:

1. What object produces visible light [in the car cabin]?
2. Why isn't a neon lamp used to produce visible light instead?
3. What other objects could produce visible light besides a light bulb?

These question types are listed in order of increasing complexity of answer generation. It is clear that a tutor must be able to answer type one. Answer generation for question type two is possible using qualitative simulation [Forbus 83], but answers for question type three require reasoning techniques that we do not yet understand.

Although we will restrict ourselves to examples of type one questions during our presentation of the different question classes, keep in mind that two other types are possible.

3.2.1 Role Group

The questions in this group are about the nature of object roles, i.e. about the nature of an object's behavior in context.

3.2.1.1 Function Performs Role

The generic question which results in the answer statement

above is: "What function performs this role?" A specific example is: "How does the light bulb illuminate the car interior?" A simple answer is the list of functions which perform the role. Since it is often difficult to distinguish between role and function, a better answer would include detail about the mechanistic implementation of the function.

3.2.1.2 Function Requires Role

This question class is harder to differentiate than the last one because it involves a level shift in the expert model hierarchy: it requests information about the functions, that are one level up in the tree and which utilize the role that is described at this level.

An example of the generic question "What function requires this role in its implementation?" is the question "Why is it important for the transmission to control power and speed?" In this case only one function requires this role: the ability to maneuver at varying speeds over different types of terrain.

The complete answer should include a statement of the higher level function whose mechanism requires this role, enough of the mechanism to illustrate the role's importance, and whatever background structural information is required to render the mechanism comprehensible.

3.2.2 Function Group

The questions in the function group deal with the black-box functionality of an object--including both teleological behavior and side effects.

3.2.2.1 Role of Function

"What is the role of this function" i.e. "Why is the engine of the car converting chemical energy to mechanical energy?"

3.2.2.2 Structure of Function

"What structural features implement the function?" i.e. "What lets the driver disengage the engine from the wheels?"

3.2.2.3 Mechanism of Function

"How do the structural features implement the function?" i.e. "How does the clutch disengage the engine from the wheels?" This class of questions usually requires only a partial mechanism description for an answer. A physical causal explanation of the specific aspect requested often is sufficient answer.

3.2.3 Structure Group

There are three aspects to structure: objects, attributes of objects and connections between objects. Since each of these aspects are explained similarly, we will only describe the object aspect.

3.2.3.1 Attribute of Object

"What is the value of this attribute for this object?" i.e. "What shape is the piston?"

3.2.3.2 Substructure of Object

"What is the substructure of this object?" i.e. "What parts are in a flashlight?" The answer should include both a list of subobjects and how they are connected.

3.2.3.3 Connection of Object

"What other objects are connected to this one?" i.e. "What is the crankshaft connected to?" The answer should include the connections and their type. The type of each connection is *especially important since it determines* what kind of interaction may occur between the objects.

3.2.3.4 Function/Role of Object

"What is the purpose of this object?" i.e. "What does the power train do?". We consider the function and role together as a question class since they are so similar. Although it is useful to distinguish between them for complete explanation generation, it is usually not worth the trouble to differentiate between them in student questions. Therefore, the best answer is the object's role and also its function (if significantly different from the role).

3.2.3.5 Mechanism of Object

"By what mechanism does this object implement its functions?" i.e. "How does a carburetor work?" These questions require a full mechanistic explanation, probably using the physical causal method (as generated by qualitative simulation) with a temporal corrective. In addition the object's functions should be stated unless the student explicitly mentioned them in the question. Also enough structural information to support the mechanistic explanation must be provided.

3.2.4 Mechanism Group

The mechanism group contains question classes which inquire about the specifics of whole mechanisms and their explanatory parts: isolated events at times and places. There are almost twice as many possible question classes as are described here, because almost every class can produce both a question about reality and a hypothetical question. For example a student could ask both: "What happens when the spark plug fires?" and "If the connecting rod broke, what would happen when the spark plug fired?" The ability to answer questions about hypothetical situations depends on extremely flexible representations of knowledge and methods for performing qualitative simulations.

3.2.4.1 Function of Mechanism

"What function does this mechanism implement?" i.e. "What is the purpose of the four stroke cycle in an internal combustion engine?"

3.2.4.2 Causal Reason for Event

"What events caused this event?" i.e. "What makes the spark plug fire?" For each precursor event set, the answer should include the active events and a causal chain showing how they make the subject event happen.

3.2.4.3 Consequence of Event

"What events are caused by this event?" i.e. "Where does the exhaust go when it is pushed from the chamber?" This class is similar to that above.

3.2.4.4 Event at Time

"What events are happening at this time?" i.e. "Where is the piston just as the spark plug is firing?"

3.2.4.5 Event at Place

"What events happen at this place?" i.e. "What happens in the cylinder?" This question class is necessary because the object hierarchy probably will not be equivalent to the spatial hierarchy, i.e. the cavity of the cylinder probably won't be a subobject of the cylinder object.

3.3 Other Issues

In this section we discuss various ramifications of the question classification scheme described above.

3.3.1 Multiple Assertions

Some questions which force multiple assertions require a different technique for answer generation. The familiar example is: "Have you stopped beating your spouse yet?" Any boolean answer to this question contains two assertions linked together by subsumption: 1) "You did beat your spouse," and 2) "You have (not) stopped."

If the subsumed assertion is incorrect, then the only proper answer is to deny the validity of the incorrect assertion: "I never beat my spouse."

3.3.2 Questions Not Captured

Our focus has been on the structure and principles of behavior of complex engineered devices, not on their design, modification, operation, or repair. Thus our taxonomy does not cover questions like: "How do I start the engine?" or "How should I replace the gasket?" To extend our taxonomy to these areas, one would need to develop a theory of human-device interaction.

Our taxonomy does not handle questions about the definition of technical terms, i.e. "What does 'compression ratio' mean?" Extending the classification scheme to handle these questions should be relatively easy.

4. CONCLUSIONS AND FUTURE WORK

We have sketched the outline for an algorithm that generates the intermediate graph form of summary explanations and answers to questions about complex engineered devices. To operate, this algorithm has the following requirements:

- A model of an expert's knowledge of the device which is: qualitative, inspectable, runnable, modifiable (i.e. distinguishes between structure and function) and hierarchical.
- A qualitative simulation engine which can predict device behavior given the expert model.
- A student model containing (at least) a record of device comprehension.

Although the algorithm looks promising, there remains much work to be done before this explanation method may be implemented and tested.

- We must investigate the utility and potential for dynamic generation or selection of graphic diagrams as a means for explaining structure and mechanism.
- Much more work is necessary to determine how to automate viewpoint selection in explanation.
- We must develop a better idea about the contents of an expert teacher's student model. New techniques must be invented so that explanations can be targeted to dispell common misconceptions.
- A more efficient implementation of a qualitative simulator is necessary to handle systems as complex as a subsystem of an internal combustion engine.

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